ELECTRIC POWER RESEARCH INSTITUTE

NDE in Nuclear Power Plants

ATR National Science User Facility - Users Week, June 7-11, 2010

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Outline

- What's NDE?
- NDE for stainless steel and nickel-alloy components (primary cooling loop materials)
  - Piping
  - Dissimilar metal welds
  - Cast stainless steel
  - Reactor pressure vessel head penetrations
- Nontraditional NDE – Things I am working on & things on the menu…
  - NDE for Concrete (new focus within the industry)
    - Spent Fuel Pools
    - Reactor Containments
    - RPV Support Pedestals
  - Pushing the limits of NDE – incipient stage damage detection
- Summary

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What's "NDE"?

- Nondestructive Evaluation
- Inspecting components to see whether they're degraded, without damaging them
  - Cracking
  - Corrosion
  - Fabrication defects
- Primary Methods
  - Ultrasound
  - X-ray radiography

  Examine the entire volume

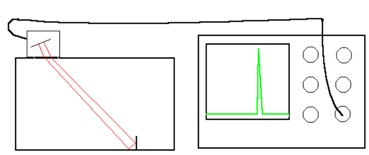
  - Eddy current
  - Dye penetrant

  Examine the surface

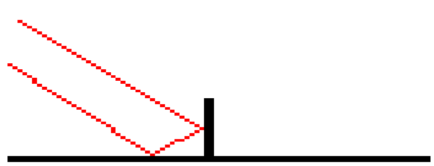
Ultrasonic examination (UT)

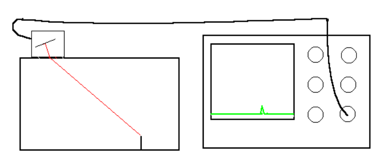
- Principle
  - Interaction of high frequency sound waves with the material (similar to sonar and medical ultrasound)
  - Reveals internal as well as surface breaking features
  - Most widely used inservice inspection method
    - Adaptable to many configurations & materials
    - Provides quantitative flaw location & sizing

Basic pulse-echo UT

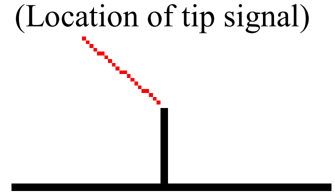


Detection
("corner echo")



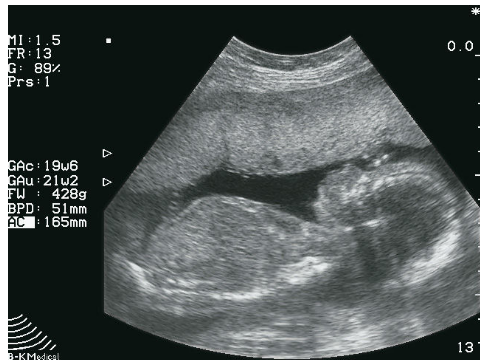


Sizing
(Location of tip signal)



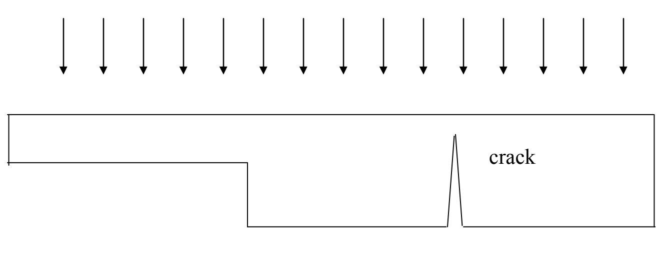
Phased Array UT

- Imaging technique similar to medical ultrasound
- Increasing in importance lately in nuclear NDE
  - Equipment is getting smaller, cheaper, and more powerful
  - Demands for speed are increasing
    - Cost
    - Low dose



Radiographic examination (RT)

- Principle
  - Density changes on film or solid state detector caused by absorption differences in a component reveal internal features
  - Volumetric method



Film image

Radiography

- Applicable to many components
- Radiological controls limit usefulness during intensive plant outage activities
  - Have to evacuate the area, disrupts other work
- Not sensitive to off-axis planar defects

Eddy current examination (ET)

- Principle
  - Interaction of electromagnetic field with the material
  - Reveals surface and very near-surface features

Eddy Current

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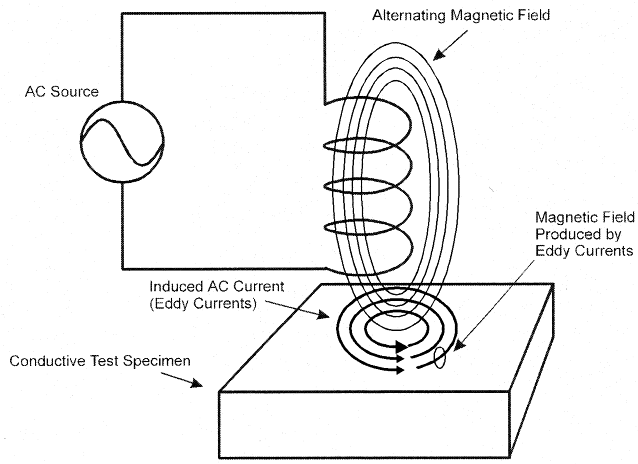
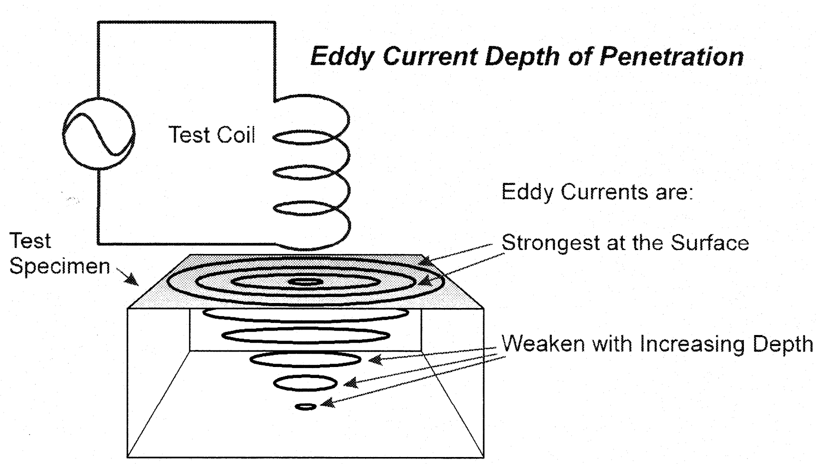
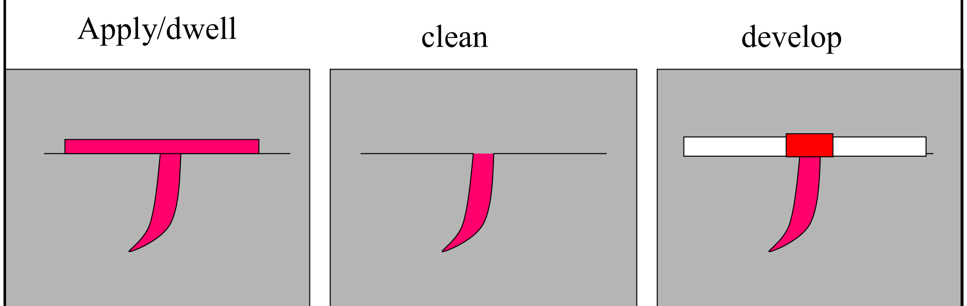


Eddy Current Principles



Liquid penetrant examination (PT)

- Principle
  - Indicator liquid (essentially, bright-red WD-40) drawn into surface breaking discontinuities by capillary action
  - Indications revealed by developer (chalky spray)
  - Strictly a surface examination method



Uncertainties

- Not all flaws that may be present will be detected
- location and sizing errors
- human errors
- NDE is only one part of the structural integrity picture
  - material properties
  - loads
  - environment

Other Reading

- Nondestructive Testing Handbook, ASNT, ISBN 0-931403-02-2
- ASM Handbook, Volume 17-Nondestructive Testing and Quality control, ISBN 0-87170-007-7
- Introduction to Phased Array Ultrasonic Technology Applications, RD Tech, Inc. ISBN 0-9735933-0-X
- Engineering Applications of Ultrasonic Time-of-flight Diffraction, JP Charlesworth and J.A.G. Temple, ISBN 0-86380-085-8

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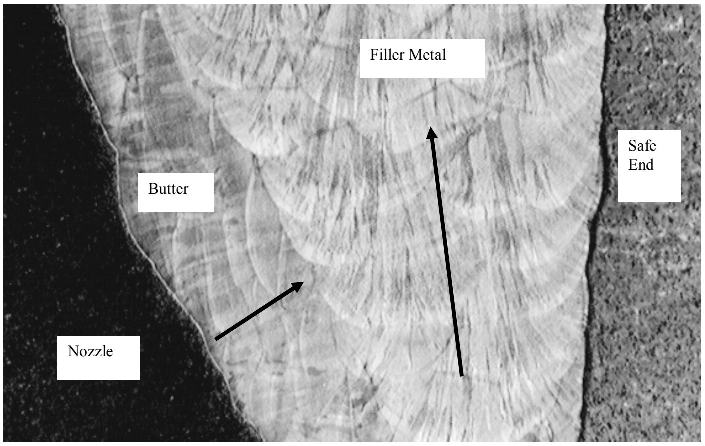
NDE of Stainless & Nickel Based Components

- Piping
  - Wrought and cast
  - Welds
  - Fittings
    - Elbows, Tees, etc
- Pump & valve bodies
- Vessel cladding & internals
- Vessel penetrations
- Steam generator and other heat exchanger tubing

UT of Stainless Steel and Nickel-based alloys

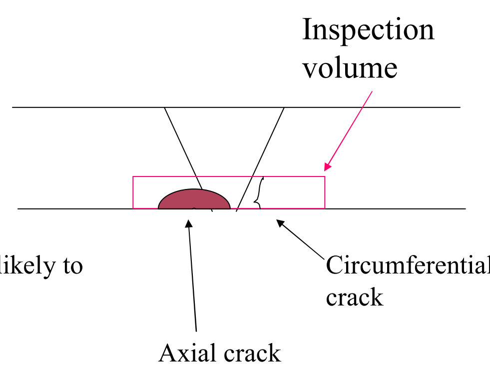
- UT is used extensively for volumetric inspection of SS & Ni based based piping welds
- Austenitic welds are acoustically anisotropic
  - Acoustic velocity is a function of beam direction with respect to the crystallographic orientation
- Each grain boundary is an impedance mismatch which causes
  - Attenuation (sensitivity loss)
  - Scattering
    - Noise
    - False calls
    - Interpretation errors
  - Re-direction of the beam can cause location errors and gaps in coverage

Dendritic Grain Structures in a Dissimilar Metal Weld



Piping Weld NDE

- Volumetric examination



Degradation mechanisms are most likely to initiate from the inside surface

•Stress corrosion cracking

•Flow assisted corrosion (FAC)

•Fatigue cracking

•Must consider the potential for axial or circumferential cracking

Intergranular stress corrosion cracking (IGSCC)

- Typically found in BWR SS piping welds and RPv internals sensitized to SCC
- Primary location is weld heat affected zone (HAZ)
  - Crack typically starts near the weld root
  - Progresses through the wall following the HAZ

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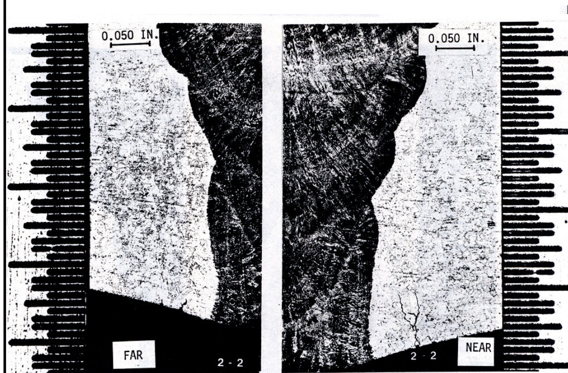
BWR Recirculation Piping-IGSCC

Typical IGSCC found in stainless steel BWR recirculation system piping

•Located in Heat Affected Zone of base metal

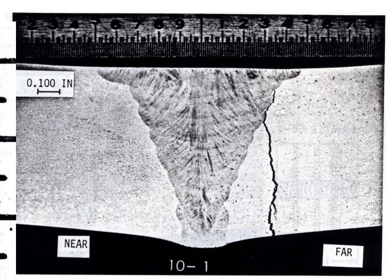
•Branched



Example of deep cracking

•Grows toward weld

•Usually follows weld profile after reaching the weld



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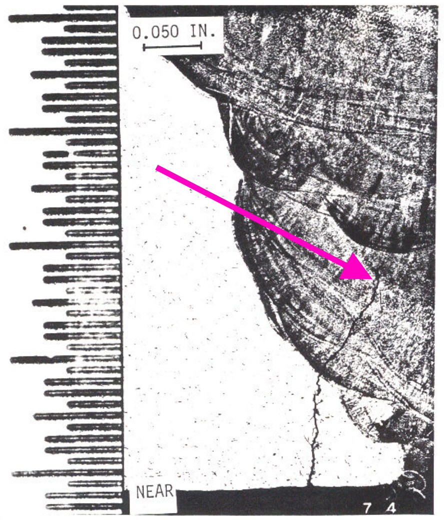
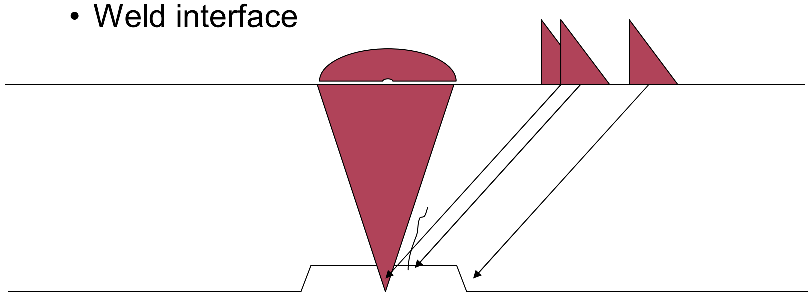
BWR Recirculation Piping-IGSCC

Example of crack growing into weld



IGSCC Discrimination
Root, Flaw, Counterbore

- UT crack detection
  - Identification of the crack signal is challenging when there are other competing signals
    - Weld root
    - Counterbore
    - Weld interface



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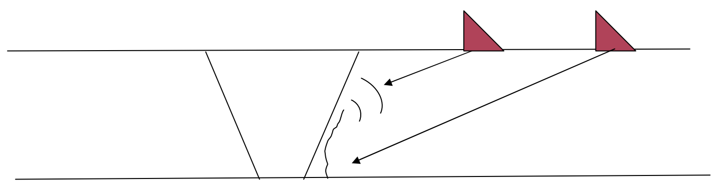
IGSCC

- Sizing is very challenging
  - Locating a diffracted wave from the crack tip
  - Difference in time-of-flight between the crack base and crack tip is used to calculate the depth
  - Experience needed to identify the tip signal



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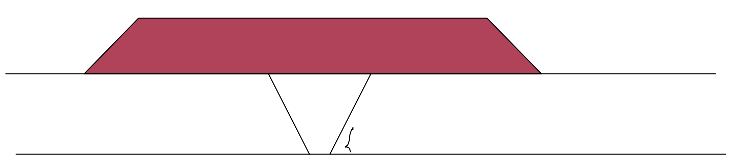
Overlay Repair

- Application of weld overlay is an effective repair method for cracked piping
  - Restores full structural integrity to a cracked pipe
  - Prevents further crack initiation and growth
- Requires good inspection after application, and continued monitoring
  - Verify integrity of the overlay itself
  - Monitor to ensure no growth of original cracks



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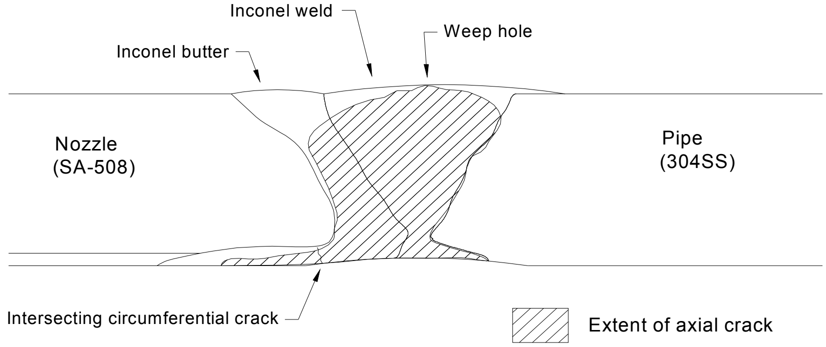
Primary water stress corrosion cracking (PWSCC) in PWR Units

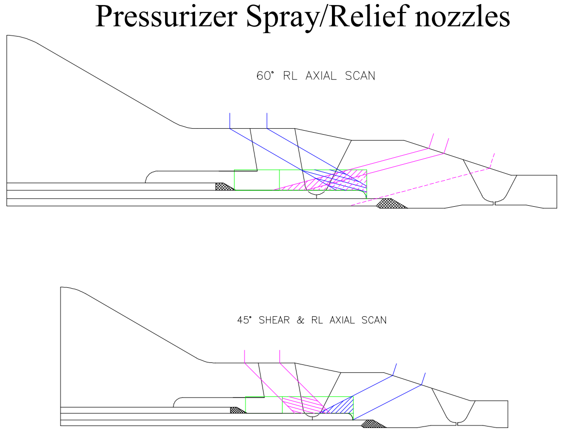
- PWSCC has been found in PWR main coolant systems with Alloy 600/182/82
- Alloy 182 welds
  - Dissimilar metal (DM) piping welds
  - Vessel head penetrations
- Alloy 600
  - Steam generator tubing

PWSCC in PWR Nozzle-Safe End Dissimilar Metal Weld at VC Summer Plant



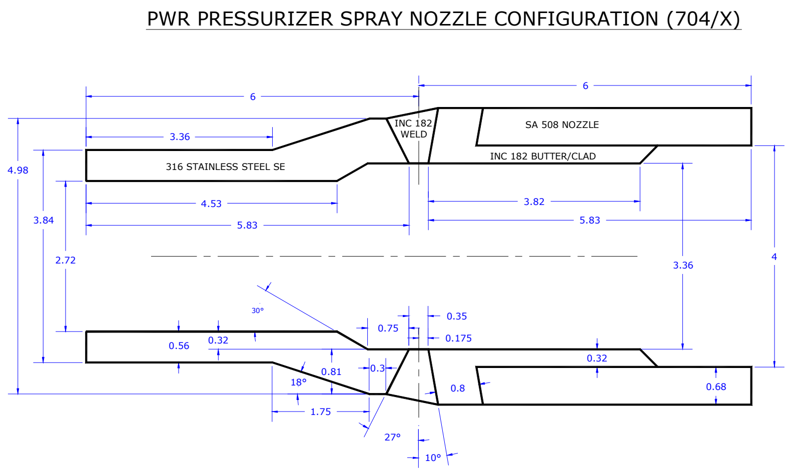
Examination of Dissimilar Metal Welds

Pressurizer Spray/Relief nozzles

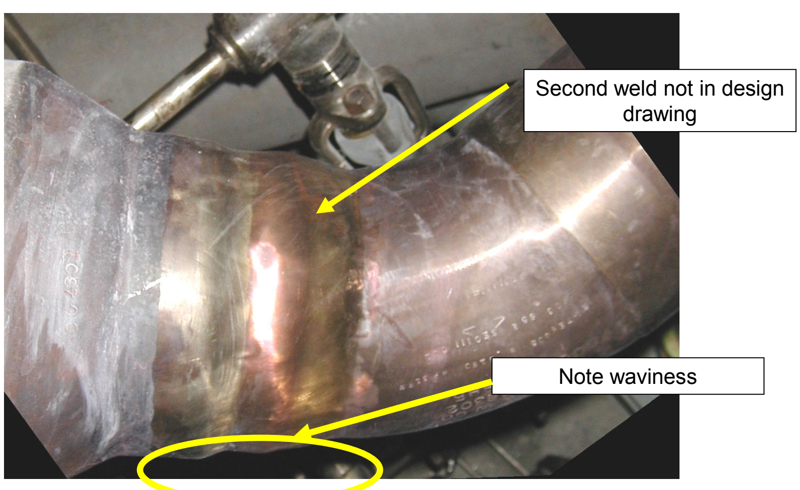


Must use a combination of probe angles and scanning surfaces to obtain coverage of the examination volume-may not get all of it

Design Drawings can't be trusted



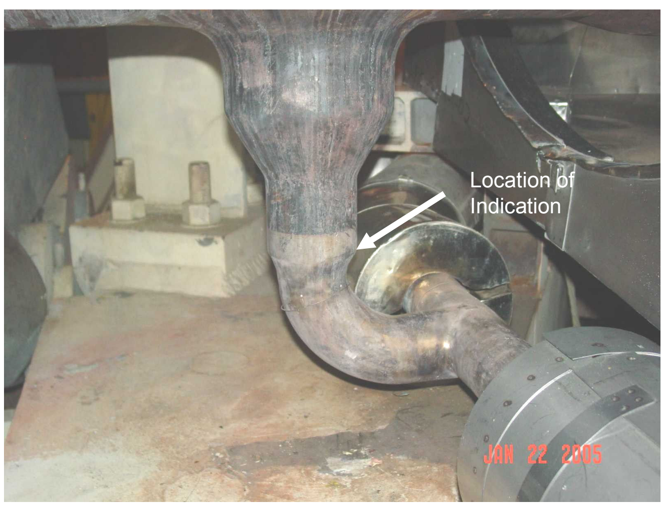
Actual Configuration



Example of a PWSCC Issue

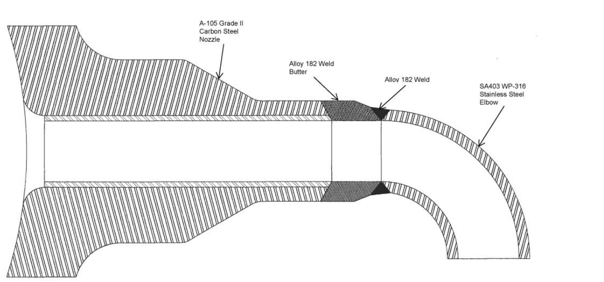
- Indication detected in a PWR cold leg drain line dissimilar metal weld
- Evaluated as a defect
- Overlay repair designed and installed

RCP 1-1 Cold Leg Drain

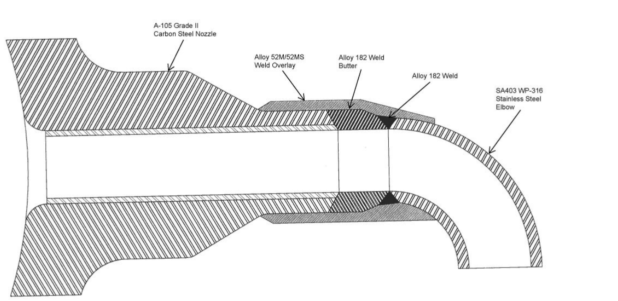


RCP 1-1 Cold Leg Drain

As-built configuration



Overlay configuration



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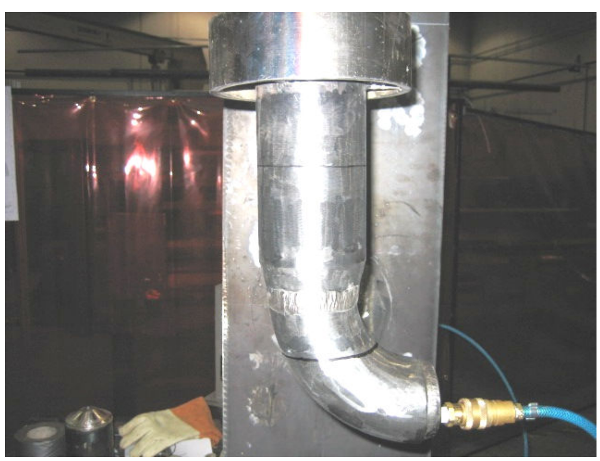
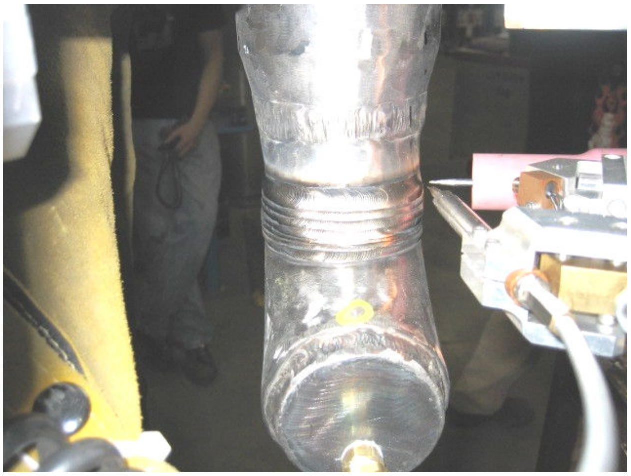


Mockup for Welding Proof of Principle
WSI Norcross, GA

RCP 1-1 Cold Leg Drain



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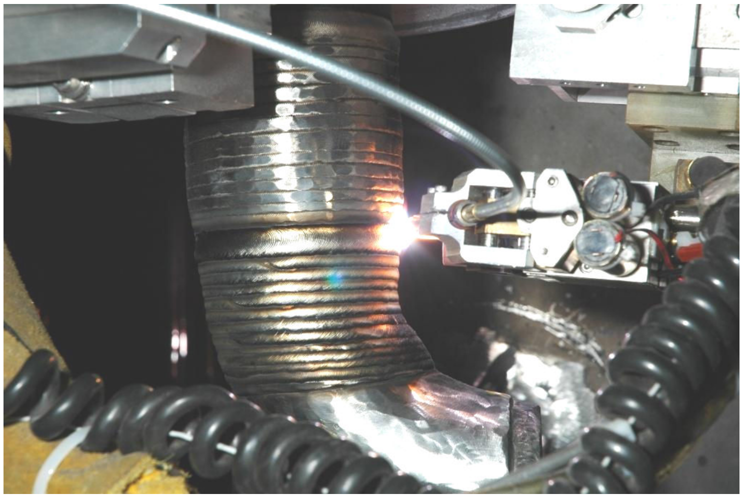

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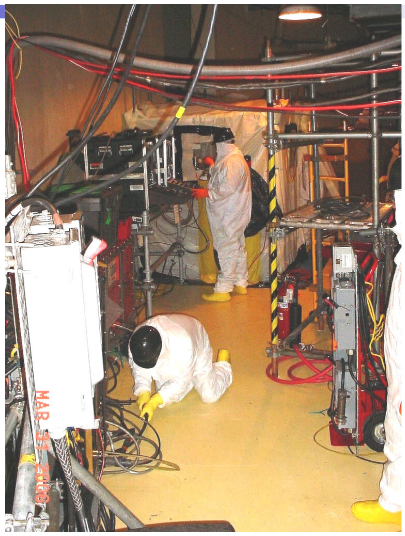
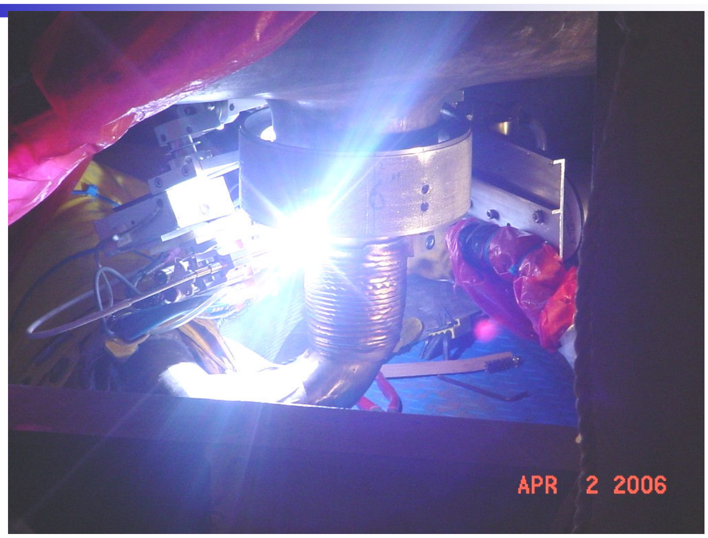


WSI Welding Power & Controls Setup

RCP 1-1 Cold Leg Drain

WSI Remote Welding Operation

RCP 1-1 Cold Leg Drain



Welding the Overlay – Day 15 After Indication Discovery

RCP 1-1 Cold Leg Drain

Final UT'd Overlay – 16 Days 6 Hours After Indication Discovery

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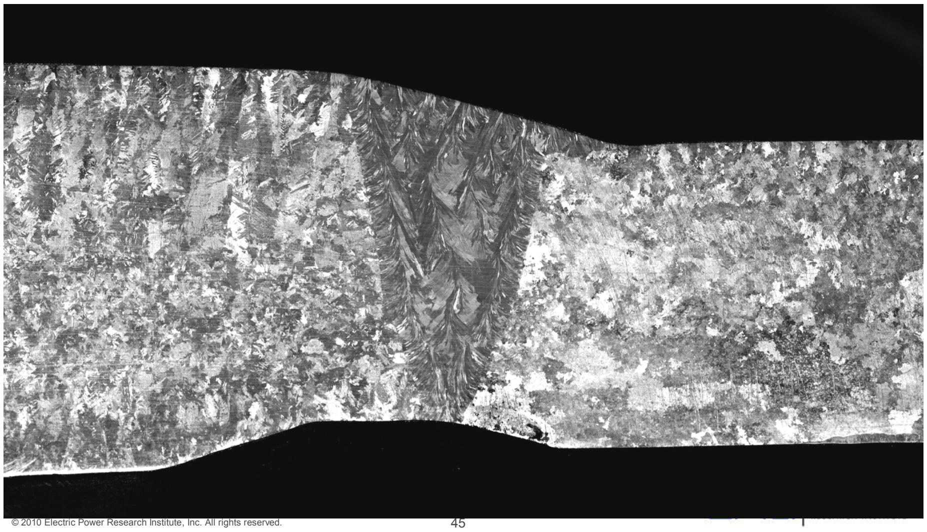
Cast Stainless Steel

- Some components are stainless steel castings
  - Pump and valve bodies, piping elbows: statically cast
  - Piping: centrifugally cast
- Castings can have very large grains
- In stainless steel, this makes UT extremely difficult because the grains are acoustically anisotropic
- Only very low-frequency sound can penetrate the metal
  - Poor resolution
  - Possibility of transmission through the face of a tight crack – no reflection, no detection
- Round-robin tests have shown that the UT capability is very poor (scanning on the outside, to detect cracking on the inside)

Cast Stainless Steel



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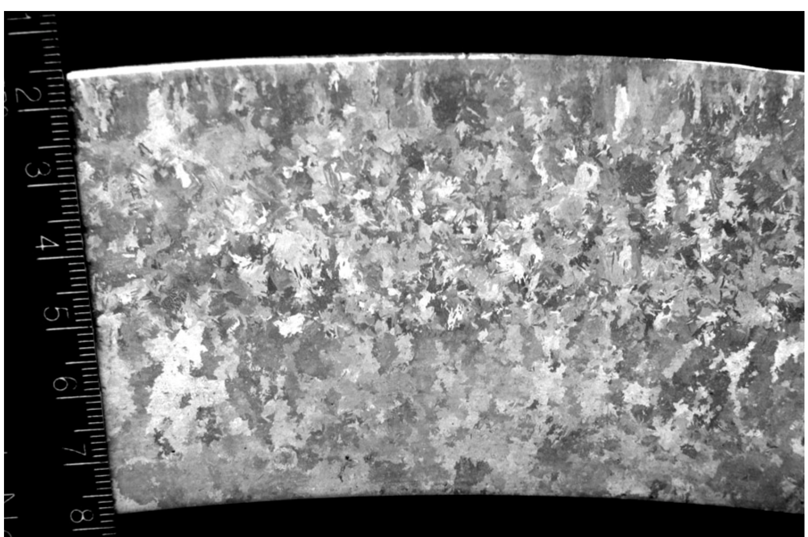

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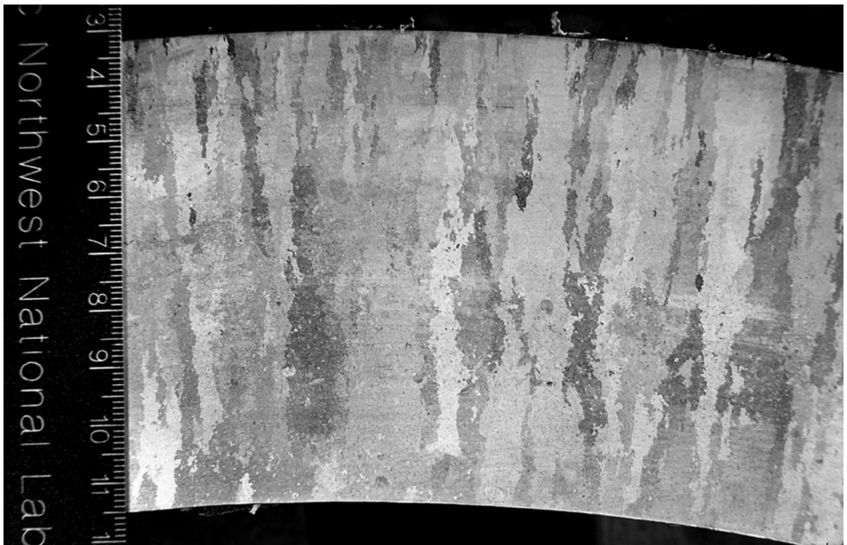

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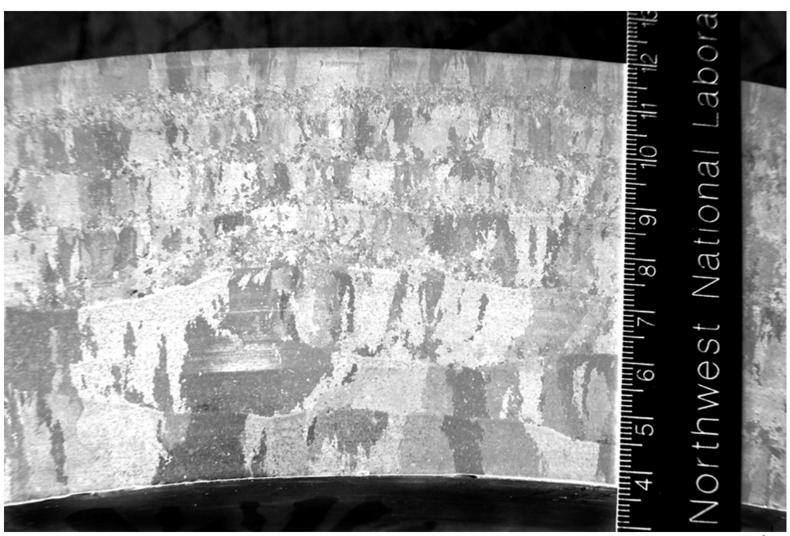

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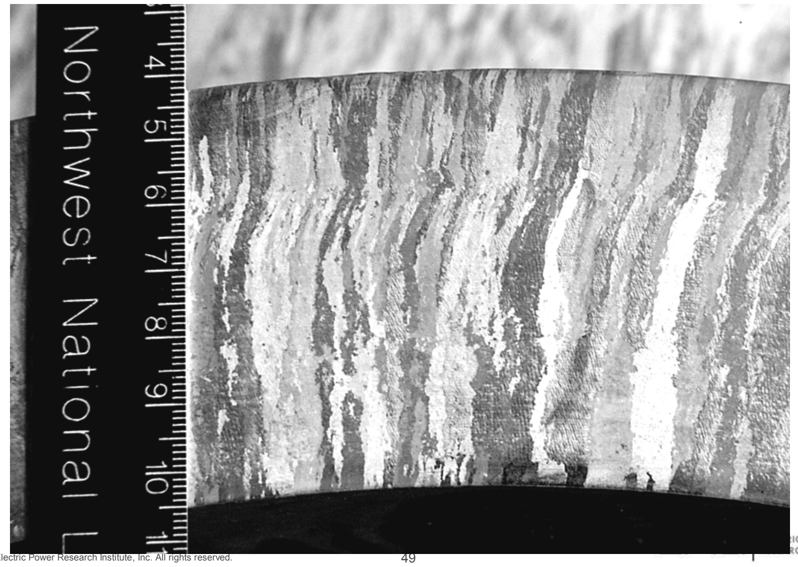
Cast Stainless Steel



Cast Stainless Steel

- No known degradation mechanism for CSS reactor coolant piping
  - No leaks
  - No failures
- No effective outside-surface UT technique is on the horizon
- Interest is growing
  - Thermal aging embrittlement
  - License renewal commitments
- Any significant effort to develop and qualify NDE will require fabrication of piping to use for mockups

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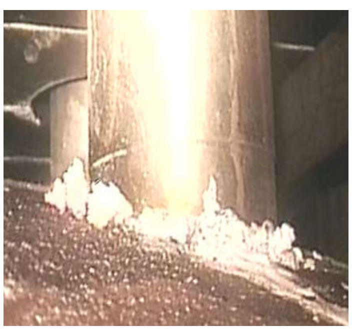
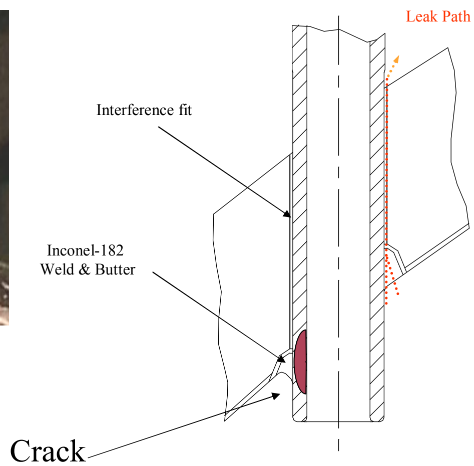
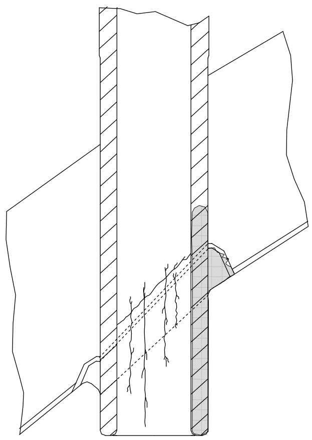
CRDM Penetration Leaks



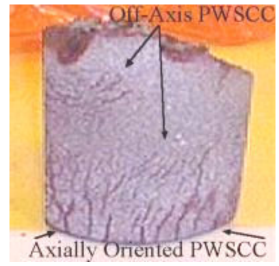
Boric Acid deposits on Top Head



PWSCC in CRDM Penetrations



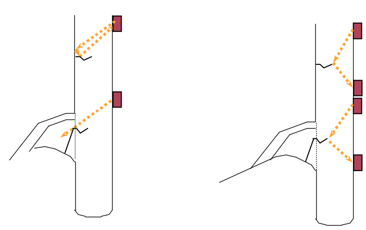
Base metal PWSCC

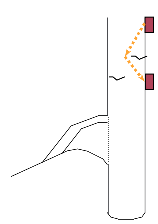


J-Groove weld cracking

Inspection of Vessel Penetrations

- UT used for detection and sizing
- ET is used in some cases for detection and length sizing
- ET used for surface examination of the wetted surfaces
- UT of the J-Groove weld has not been proven reliable-many sources of false calls





Summary

- Inspection of stainless steel and Nickel based materials presents challenges
  - Anisotropy
  - Geometry
  - Access
  - High radiation areas
- Many of these problems can be overcome with proper advance knowledge of the configurations
  - Allow time for planning, training, and qualification of the process
- Gaps in the NDE technology remain
  - Welds with excessively wavy surfaces
  - Cast stainless steel
  - Volumetric examination of the J-groove welds in vessel head penetrations

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EPRI LTO Program

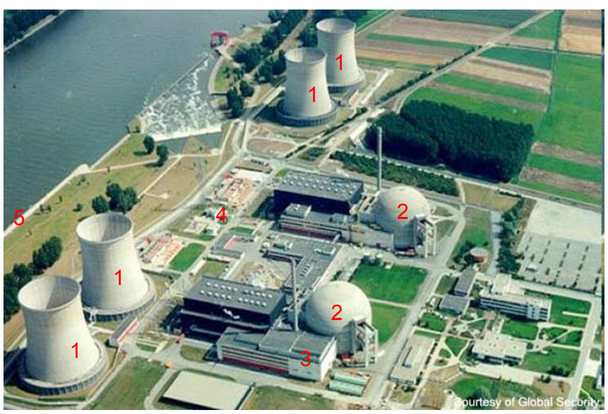
The goal of the LTO Program is to conduct R & D looking to problems that might be encountered during 40 – 60 – 80 years of operation.

Reinforced concrete civil structures are one of the primary focuses for LTO. Failure of such structures have the potential to terminate the operational life of the plant.

EPRI has partnered with EDF, the MAI and ORNL to develop a long term research agenda for aging in concrete structures.

Structures of Interest

2 Unit Nuclear Plant (PWRs)



1 – Cooling Towers
2 – Containments
3 – Spent Fuel Pools
4 - Buried Pretensioned Concrete Pipe
5 – Intake Structure

Leaking Spent Fuel Pools in PWRs

September 2002, Salem generating station reported evidence of radionuclide contamination through an interior wall in the Unit 1 Aux. Bldg.

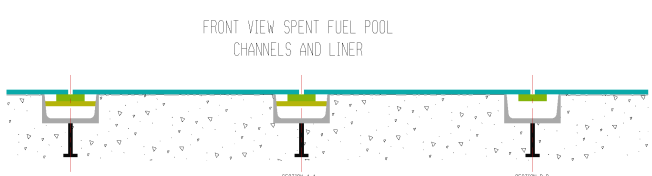
In 2003 Salem reported tritium contamination of the groundwater within the limits of the plant restricted area. A task force was established to find the source of the contamination.

It was established that the contamination in both cases was due to leakage of water from the spent fuel pool.

Leaking Spent Fuel Pools in PWRs

Groundwater contamination was the result of obstruction of the drainage system by quartz and calcite.

This resulted in filling of the drainage channels and a hydrostatic head which forced water through the construction joints.



Leaking Spent Fuel Pools in PWRs

- The licensee hopes to operate during the period of license renewal (40 – 60 years) with the leak since liner repair/replacement is unfeasible.
- The licensee had to make a case to the US NRC that SFP leakage would not be a structural or groundwater contamination issue for operation to 60 years.
- The conditions seen in Salem are typical of PWR spent fuel pools. Many of them are leaking..

LTO ISSUE: At what point in time does this become a structural issue (e.g., attack of the rebar)???

Leaking Spent Fuel Pools in PWRs

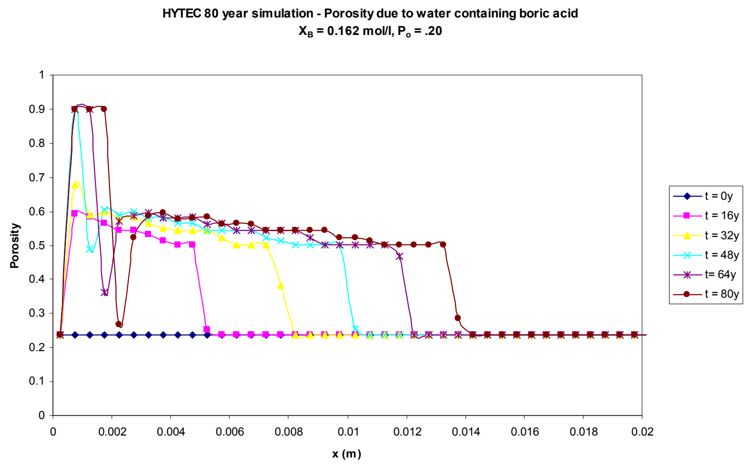
Neutralization of $B(OH)_3$ in Portland cement occurs by:

$$Ca(OH)_2 + 2(B(OH)_3) = Ca(H_2BO_3)_2 + H_2O$$

Model the degradation rate due to reaction of boric acid in Portland cement using HYTEC (coupled thermodynamics / kinetics computational model). This yields an effective diffusivity for degradation, D_{eff}.

Variables: concentration of boric acid in water, porosity.

Leaking Spent Fuel Pools in PWRs



Outline

- What's NDE?
- NDE for stainless steel and nickel-alloy components (primary cooling loop materials)
  - Piping
  - Dissimilar metal welds
  - Cast stainless steel
  - Reactor pressure vessel head penetrations
- Nontraditional NDE – Things I am working on & things on the menu…
  - NDE for Concrete (LTO: A new industry focus)
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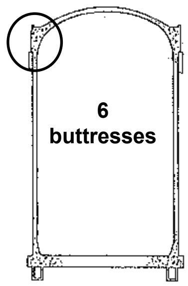
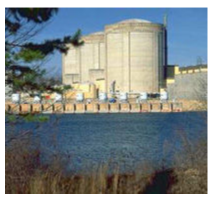
    - **Reactor Containments**
  - Pushing the limits of NDE – incipient stage damage detection
- Summary

Containment Delamination

10 US Reactors

3-D Post Tensioned concrete containment





In 2009, during SGR activities, extensive delamination was discovered in the wall of the Crystal River 3 containment.

Progress Energy is working to assess the root cause, impact to structural integrity and define repair requirements.

EPRI was asked to evaluate the containment inspection methods and procedures employed at CR3.

Containment Delamination

Retracted

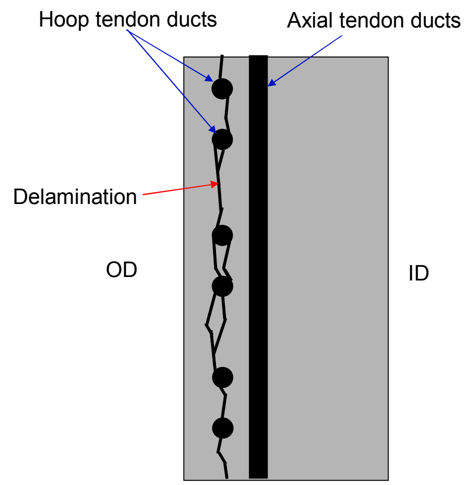
Containment Delamination

Inspection methods evaluated for this issue:

- *Impulse Response*
- *Impact Echo*
- *Ground Penetrating Radar*
- *MIRA*

The inspection proceeded using impulse response, ground penetrating radar.

Coring and boroscopy were used for field calibration and confirmation.



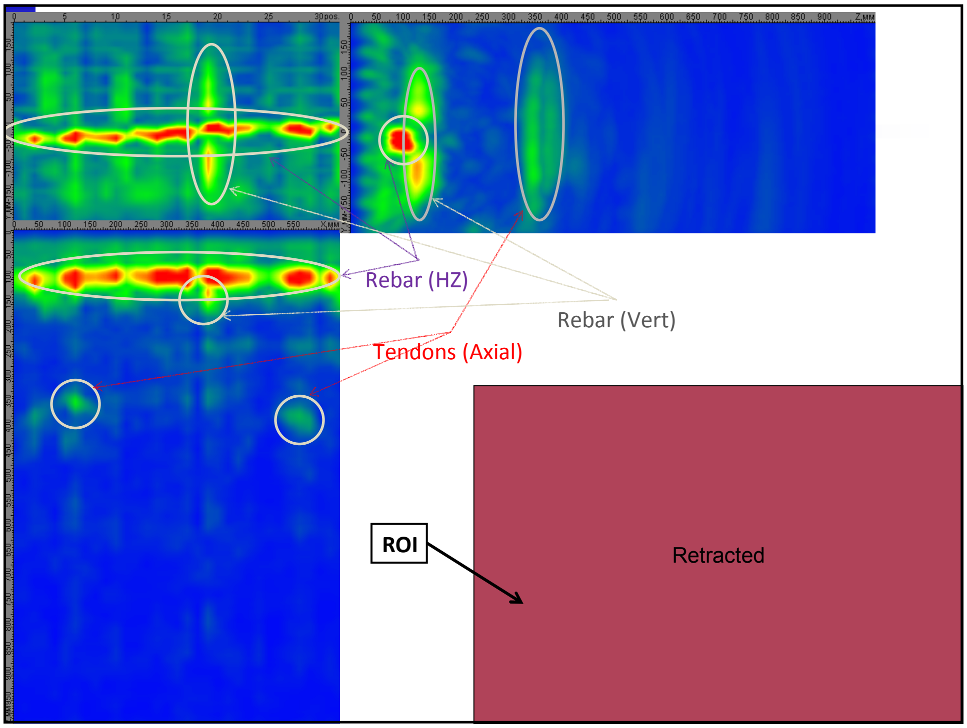
CR3 MIRA Measurements (J. Wall)

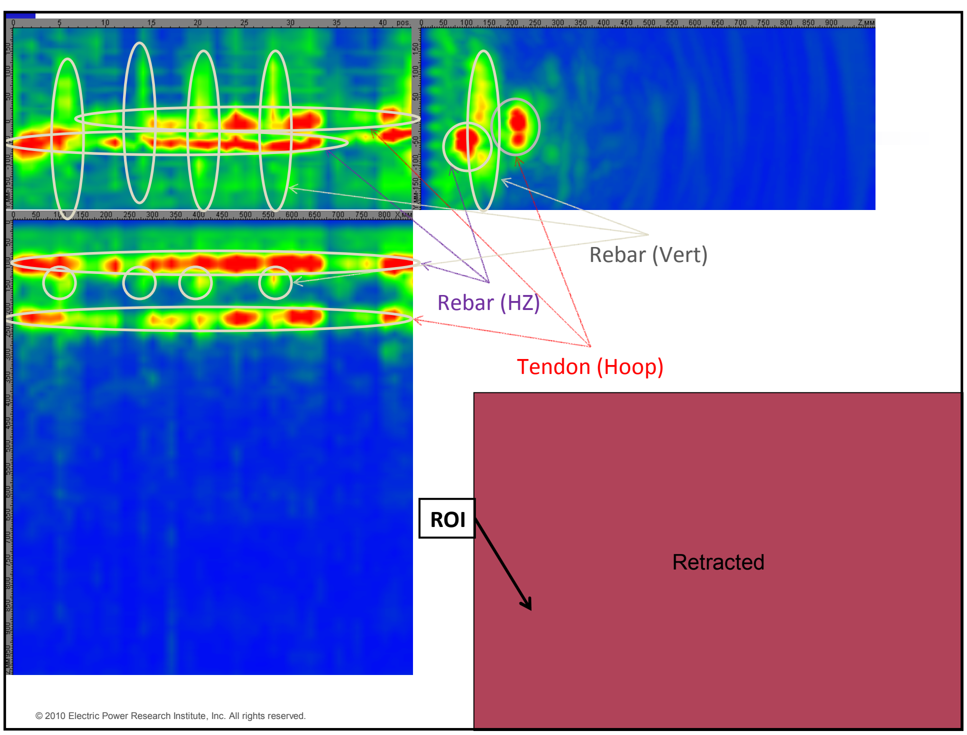
1st slide shows undelaminated containment section (200 mm x ~ 1m) – area adjacent to hoop tendon

2nd slide shows undelaminated containment section (200 mm x ~ 1m) – area directly above hoop tendon.

3rd and 4th slides show delaminated sections to either side of the SGR opening – only a few data points due to poor accessibility.

Note – ROI denotes area where measurements were taken


Rebar (HZ)
Rebar (Vert)
Tendons (Axial)
ROI
Retracted


Rebar (Vert)
Rebar (HZ)
Tendon (Hoop)
ROI
Retracted
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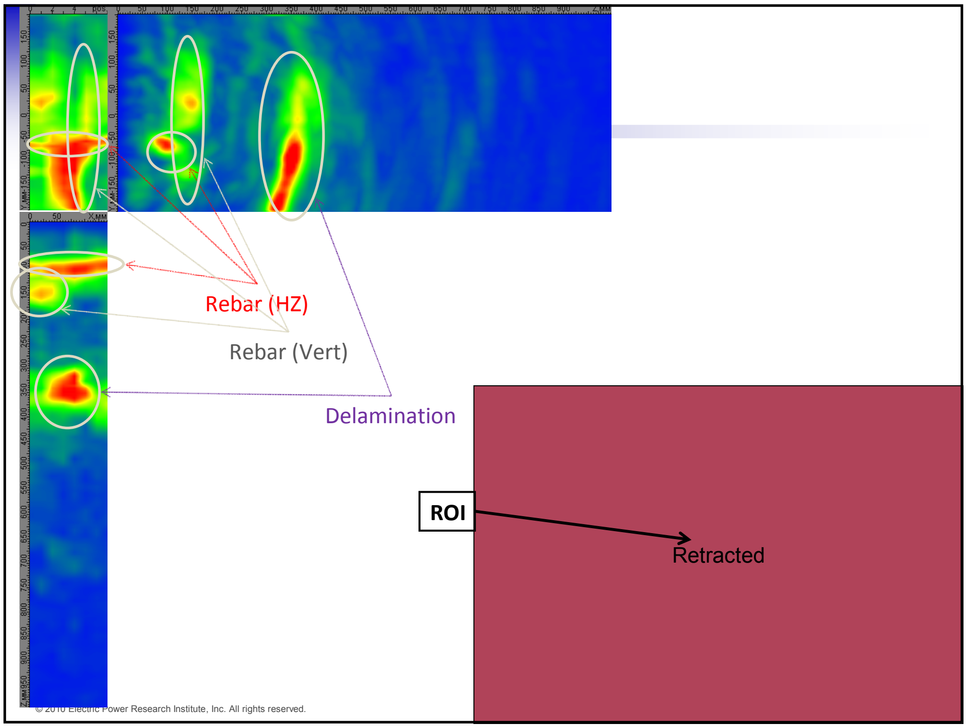
Rebar (HZ)
Rebar (Vert)
Delamination
ROI
Retracted
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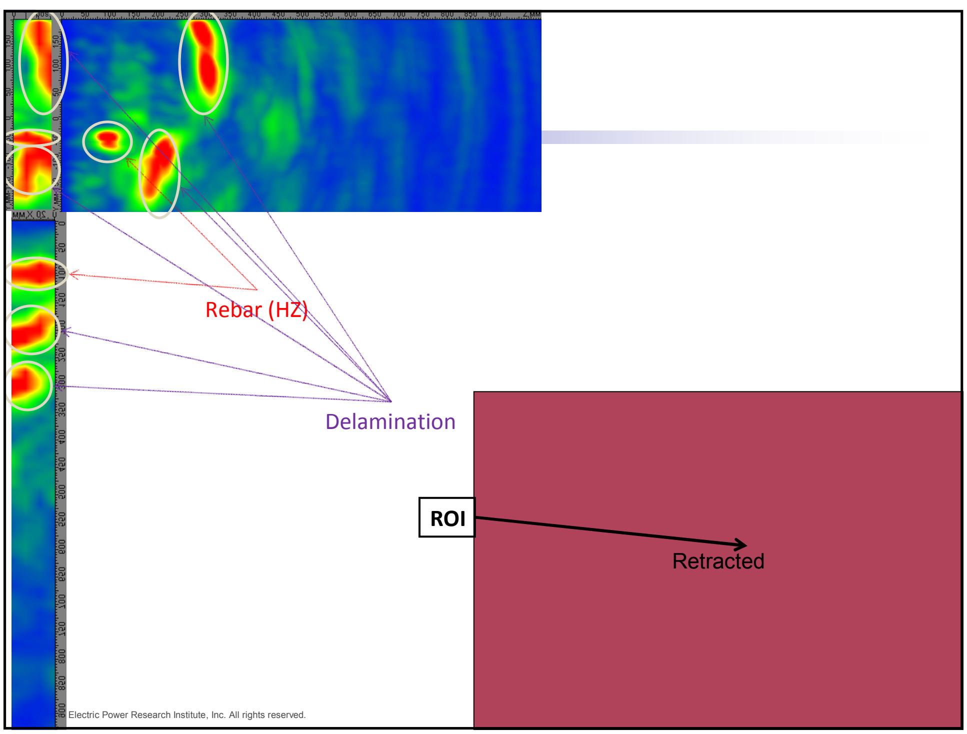
Rebar (HZ)
Delamination
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Retracted
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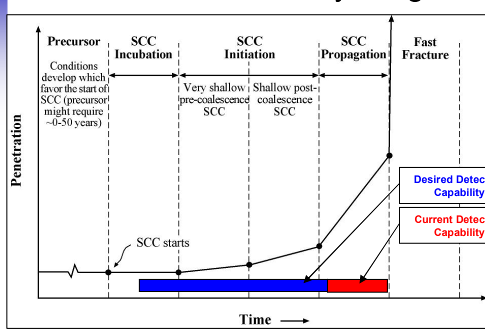
Detection of Early Stage Cracking or Creep Damage



Current NDE Technology is only sufficient to detect damage during its final stages.

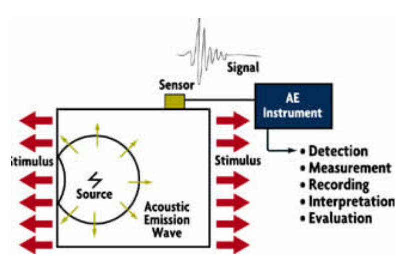
This project seeks to allow earlier detection of mechanical damage to components in NPPs.

METHODOLOGY

•Build a mechanical testing laboratory to subject samples to temperature and stress and study damage in-situ using, e.g., acoustic emission.

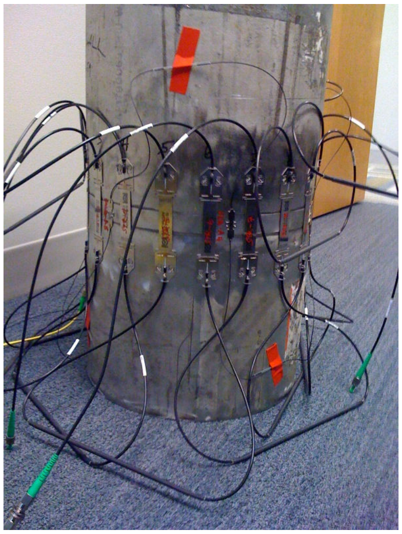
•Develop techniques to predict susceptibility of materials to damage, e.g., coercive force.

•Pursue technologies further based on results.



Long term Value to Members is Better Component Management and Fewer Inspections

In-Situ SCC Test Using Bragg Fiber Grating Strain Sensors



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Summary - overall

- NDE is used extensively in nuclear power plants. To date, the majority of NDE has been focused on primary loop components.
- Long term operation of nuclear plants will require the adoption of NDE for civil infrastructure. EPRI is actively engaged in this.
- The future of NDE in the nuclear industry will be to detect damage at earlier stages.